

# Flash-ionization of pre-existing circumstellar material around Nova Oph 2015

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## ABSTRACT

We have obtained daily high resolution Echelle spectroscopy of Nova Oph 2015 during its initial evolution. It reveals the presence of pre-existing circumstellar material around the nova, which is best interpreted as the wind of an evolved companion. On earliest observations, the emission line profiles of Nova Oph 2015 displayed a very narrow emission component ( $\text{FWHM} \sim 60 \text{ km sec}^{-1}$ ), recombining over a time scale of 5 days and showing constant low velocity ( $\text{RV}_\odot = -4.5 \text{ km sec}^{-1}$ ), that we interpret as coming from the wind of the secondary recombining after the ionization from the initial UV-flash of the nova. The underlying broad component underwent a marked reduction in both FWHM and width at zero intensity (the latter declining from 4000 to 2000  $\text{km sec}^{-1}$  in ten days) while increasing by 6× in flux, that we believe is the result of the high velocity ejecta of the nova being slowed down while trying to expand within the surrounding wind of the companion. Novae with evolved secondaries are very rare in the Galaxy, amounting to  $\sim 3\%$  of the total according to recent estimates. Among them Nova Oph 2015 is perhaps unique in having displayed a long rise to maximum brightness and a slow decline from it, a FeII-type classification (contrary to prevailing He/N) and a probable sub-giant luminosity class for the secondary (instead of the giant (e.g. RS Oph) or supergiant (e.g. V407 Cyg) class for the others).

**Key words:** Stars: novae

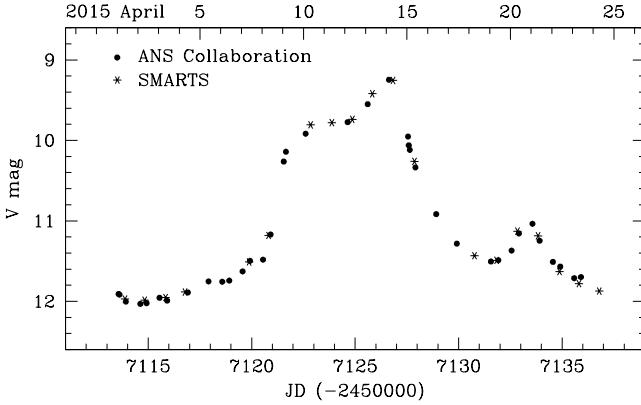
## 1 INTRODUCTION

Nova Oph 2015 was discovered by Y. Sakurai (Japan) on Mar 29.766 UT at unfiltered  $\sim 12.2$  magnitude (cf CBET 4086) and received the designation PNV J17291350-1846120 when posted at the Central Bureau for Astronomical Telegrams's TOCP webpage. Spectroscopic observations on Mar 30 by Fujii (2015) and Ayani (2015), and on Apr 2 by Danilet et al. (2015) showed the new transient to be a nova. Their classification was “He/N” type. However, at the time of these early spectroscopic observations the nova was still  $\sim 3$  mag below maximum brightness and spectroscopic observations obtained around maximum on Apr 11 by Munari et al. (2015) revealed instead a textbook example of a “FeII” type nova dominated by a reddened and strong continuum, with intense emission lines from Balmer, FeII, CaII and OI, all showing deep P-Cyg absorptions. None of the HeI, NII and NIII emission lines distinctive of an ‘He/N’ type was present.

During their initial rise in brightness, the expanding photospheres of FeII novae cool from the initial extremely high temperatures (at the time when the electron degeneracy is lifted) to the  $\sim 8000$  K characteristic of maximum op-

tical brightness, and in doing this they have to pass through the hotter temperatures characteristic of He/N-type spectra (Seitter 1990), which seems a plausible explanation for the apparent conflict in the spectral classifications of Nova Oph 2015. This should not be confused with the rare and still unclear phenomenon of *hybrid*-novae (Williams 1992), where features typical of *both* He/N and FeII types are simultaneously present and independently evolve during the *post-maximum* decline. A FeII classification also fitted the IR observations of Nova Oph 2015 by Banerjee et al. (2015), although they noted that for a brief period HeI lines were stronger than usual for this type of nova. Here it is worth reminding that the FeII and He/N classification scheme introduced by Williams (1992) is applicable to novae only around maximum brightness and early decline from it.

Classical novae are compact binaries, typically of a few hours orbital period, wherein a low-mass unevolved star that fills its Roche lobe transfers material to a more massive white dwarf companion. The transfer through L1 occurs at a low rate and little matter is dispersed into the circumstellar environment (Warner 1995, Hellier 2001). The fast evolving thermonuclear runaway that initiates the nova outburst increases (in a matter of minutes) the effective temperature



**Figure 1.** *V*-band photometric evolution of Nova Oph 2015, covering the rise to maximum and initial decline.

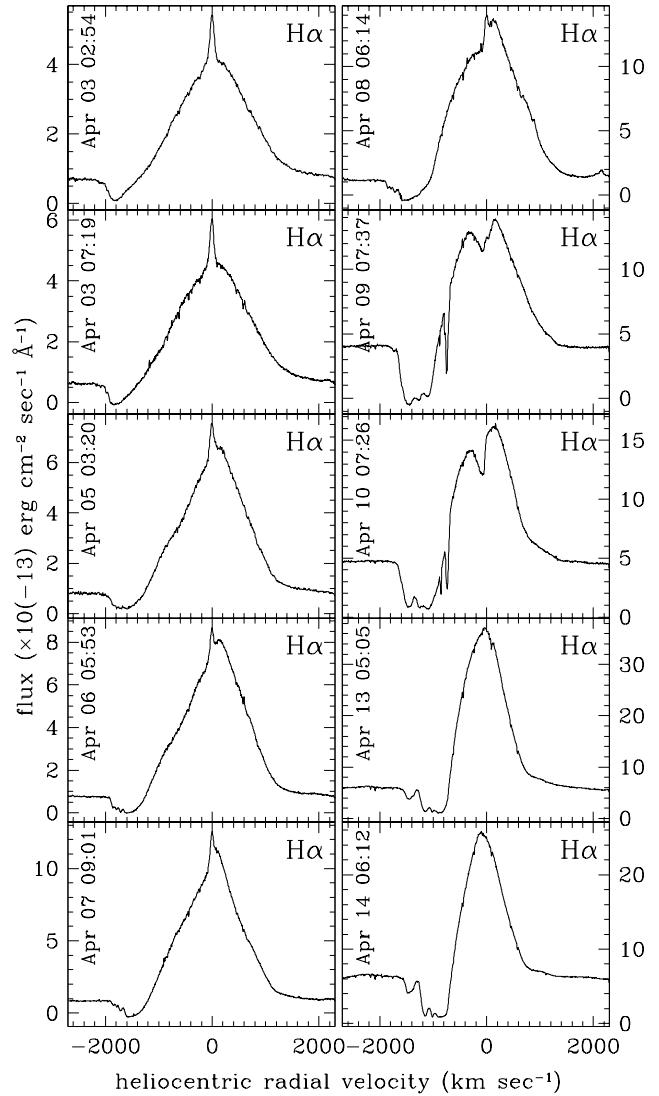
of the white dwarf envelope to several  $10^5$  K (Starrfield et al. 2008), before the violent expansion following the lifting of the electron degeneracy drives it through a rapid cooling. The short-lived surge in effective temperature produces a powerful UV flash that disperses into the empty circumstellar environment emptiness and goes undetected; the nova will be discovered only a few days later when the optically thick ejecta will have expanded enough to become a bright optical source.

There is however a very rare type of nova ( $\sim 3\%$  of the total, Williams et al. 2014) in which the initial UV flash interacts with dense pre-existing circumstellar material, the prototypes being the recurrent novae RS Oph and V407 Cyg (Evans et al. 2008; Munari et al. 2011). In such systems, the WD orbits - with periods of a few years - within the extended wind of a late type giant companion. Such a wind is able to completely absorb the initial UV flash, become largely ionized, and shine for several days during the following recombination. In this letter we present evidence that Nova Oph 2015 is a new member of this highly exclusive club of novae with evolved secondaries. In some equally rare novae, the initial UV flash manifested itself at much later times. In Nova Vul 2007, about one year past eruption, the UV flash reached and ionized gas blown off by the WD progenitor about 14 000 yrs earlier (Wesson et al. 2008). Several months after the 2011 outburst of the recurrent Nova T Pyx, the UV flash reached and ionized blobs of material ejected during the previous outburst (Shara et al. 2015).

## 2 OBSERVATIONS

High-resolution spectroscopic observations of Nova Oph 2015 were obtained with telescopes SMARTS 1.5m + CHIRON from CTIO (Chile), with 1.82m + REOSC Echelle from Asiago and with 0.61m + Astrolight Instruments mk.III Multi-Mode Spectrograph from Varese. Given the low target altitude above the horizon for observation from Italy, the spectra from Asiago and Varese were obtained with a 2-arcsec wide and 20-arcsec long slit aligned along the parallactic angle, while SMARTS 1.5m telescope uses a 1.5-arcsec diameter fiber to feed light to CHIRON spectrograph (Tovokin et al. 2013).

Optical photometry of Nova Oph 2015 was obtained



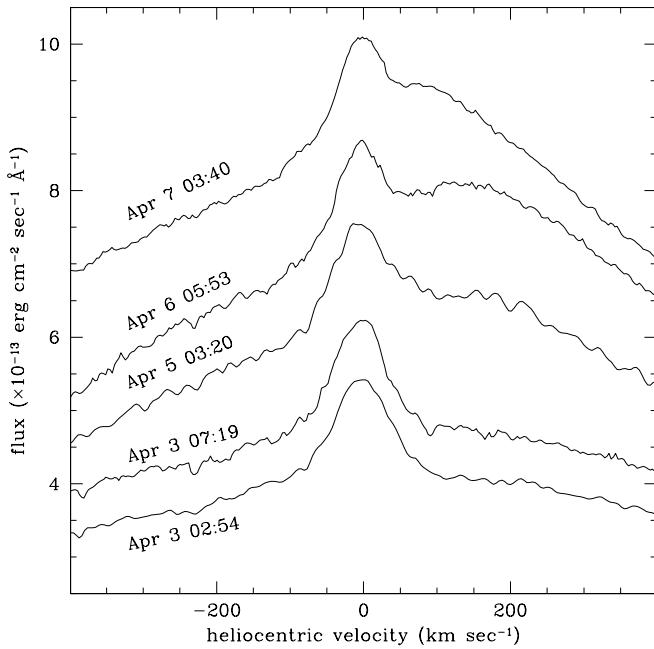
**Figure 2.**  $H\alpha$  profile evolution of Nova Oph 2015, covering the rise to maximum (occurring on Apr 14.2 UT). The UT date of each spectrum is given.

with (i) ANS Collaboration telescopes 30 (Cembra, Italy) and 210 (Atacama, Chile) and reduced against a local photometric sequence extracted from all-sky APASS survey (Henden et al. 2012, Munari et al. 2014), and (ii) with SMARTS 1.3-m + ANDICAM from CTIO (Chile), and reduced against nightly observations of all-sky standard stars (Walter et al. 2012).

## 3 EMISSION LINE PROFILES

The photometric evolution of Nova Oph 2015 during its rise toward maximum brightness is shown in Figure 1. The rise was slow, with a pre-maximum halt lasting a week while the nova was 2.5/3.0 mag below maximum. The maximum was reached at  $V \sim 9.25$  mag around Apr 14.2 UT (2457126.7), two weeks past initial discovery.

The evolution of the  $H\alpha$  line profile during the rise toward maximum is illustrated in Figure 2 ( $H\beta$  and  $H\gamma$  evolved



**Figure 3.** Expanded view of some of the H $\alpha$  profiles from Figure 2 to highlight the narrow component superimposed to the broader one. An offset in flux (-2.7 units) has been applied to Apr 7 03:40 spectrum to better fit the figure.

similarly). Apart from the complex system of P-Cyg absorptions typical of FeII novae, the profile evolution is characterized by (*i*) the initial presence of a very narrow component, and (*ii*) the monotonic reduction in width of the underlying broad component, in particular the gradual suppression of the high velocity wings.

### 3.1 The narrow component

A narrow component has been seen during the earliest phases of a nova outburst only for those erupted in symbiotic binary system, like RS Oph and V407 Cyg, where the WD is engulfed by the wind of the late type giant companion. This narrow component should not be confused with a similar feature observed in a small group of novae (KT Eri, YY Dor, LMC 1990b, LMC 2009a, V394 Cra, U Sco and DE Cir) much later in the evolution and that is believed to originate either from projection effect of bipolar ejecta or from the unveiling of the central binary that has resumed accretion (Walter et al. 2012, Mason & Walter 2013, Shore et al. 2013, Mason & Munari 2014, Munari, Mason, & Valisa 2014).

The narrow component is visible in Nova Oph 2015 for the first six days of our monitoring (cf Figure 2), during which its heliocentric radial velocity remains constant within 2 km sec $^{-1}$  (essentially the measurement error) of the average value  $-4.5 \text{ km sec}^{-1}$ . The narrow component has a Gaussian profile (cf Figure 3) with a FWHM  $\sim 60 \text{ km sec}^{-1}$ . The evolution with time of the integrated flux of the narrow component is plotted Figure 4 (top panel). It shows a steady decline, with a  $1/e$  recombination time scale of  $t_{\text{rec}}=5$  days. In analogy with RS Oph and V407 Cyg, we interpret the narrow component as originating from the wind of the secondary recombining after the sudden ionization caused

by the initial UV-flash. In this context, the FWHM of 60 km sec $^{-1}$  nicely fits the expectation from the slow wind of an evolved star and the  $-4.5 \text{ km sec}^{-1}$  heliocentric radial velocity corresponds to that of the cool giant (combining galactic and orbital motions). The recombination time scale (in hours) is related to electronic density ( $n_e$ ) and temperature ( $T_e$ ) by

$$t_{\text{rec}} = 1.15 \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.8} \left( \frac{n_e}{10^9 \text{ cm}^{-3}} \right)^{-1} \quad (1)$$

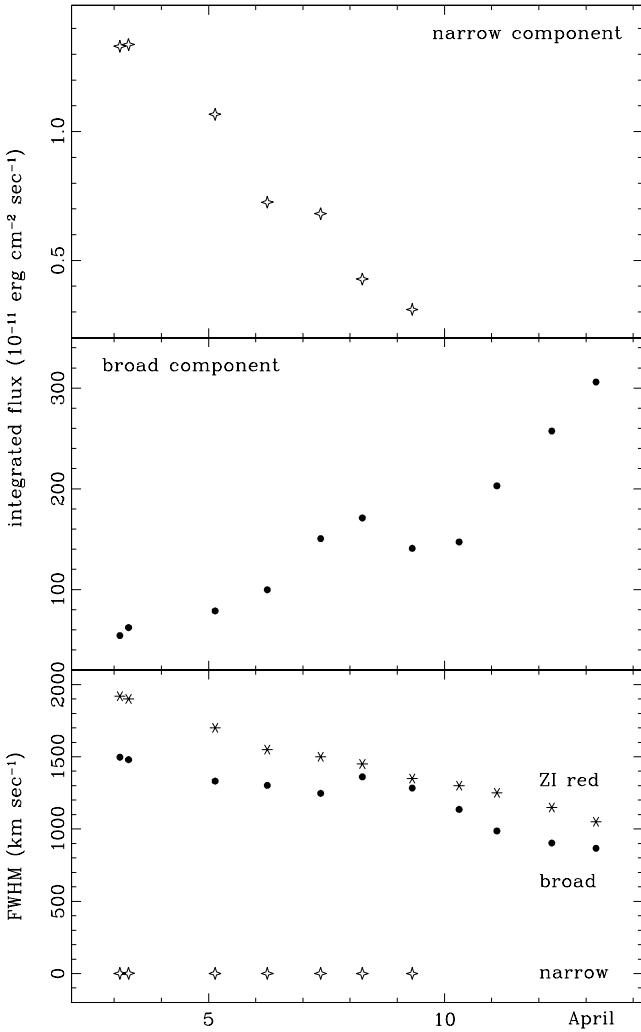
(Ferland 1997), to which correspond a density of  $n_e=1\times 10^7 \text{ cm}^{-3}$  for a typical  $T_e=1\times 10^4 \text{ K}$ , a value of  $n_e$  similar to that derived for the winds in RS Oph and V407 Cyg.

A major difference with RS Oph (Skopal et al. 2008) and V407 Cyg (Munari et al. 2011), is the lack of an even sharper absorption superimposed to the narrow component. This very sharp absorption (FWHM  $\sim 15 \text{ km sec}^{-1}$ ) originates in the outer neutral portion of the wind not reached by the initial UV-flash, which is completely absorbed by the gas inner to it. The lack of an external neutral zone suggests that the wind of the companion in Nova Oph 2015 extends much less than in RS Oph or V407 Cyg, i.e. the evolved star in Nova Oph 2015 is of lower luminosity and/or earlier spectral type. This argument is reinforced by noting that the eruption of Nova Oph 2015, of FeII type, was probably much less energetic than those of RS Oph and V407 Cyg, both of the He/N type.

### 3.2 The broad component

The evolution of the width and the integrated flux of the broad component of H $\alpha$  is shown in Figure 4. It is characterized by a continuous sharpening of the profile and a parallel continuous increase of its integrated flux. In principle, the sharpening could be the result of the ejecta's pseudo-photosphere cooling because of the expansion: the decreasing number of emitted ionizing photons is unable to reach and ionize more distant - and therefore faster moving - ejecta. This scenario requires however a parallel *reduction* in the integrated flux because of the decreasing amount of ionized gas. The very fact that the broad component of H $\alpha$  instead *increased* its flux by  $6\times$  during the sharpening period (cf Figure 4), argues for the latter being caused by a deceleration of the expanding ejecta. This would be caused by the ejecta's expansion within the wind of the evolved companion, with the resulting shock sustaining the ionization of the swept up material. The measurement of the FWHM of the broad component is grossly perturbed by the P-Cyg absorption components on the blue side, so we have also measured the velocity at zero intensity of the red wing of H $\alpha$  (unperturbed by absorptions), and plotted it as ZI-red on the bottom panel of Figure 4.

The ZI-red velocity halves, from  $\sim 2000$  to  $\sim 1000 \text{ km sec}^{-1}$ , during the 11 days of pre-maximum phase. The ejecta first slamming onto the slow-moving pre-existing wind are those moving at higher velocities and responsible for the emission in the wings of H $\alpha$  profile, which are rapidly suppressed, as clearly illustrated in Figure 2. A closely similar profile-sharpening and wing-suppression was observed in V407 Cyg, where H $\alpha$  took 5 days to half its FWHM (Munari et al. 2011). After maximum brightness, the ZI-red velocity of H $\alpha$  did not change significantly, remaining close to  $\sim 1100$



**Figure 4.** Evolution in integrated flux and FWHM for the H $\alpha$  narrow and broad components. ‘ZI red’ is the velocity at zero intensity of the red wing of H $\alpha$ , unperturbed by the P-Cygni absorptions that plague the blue one.

km sec $^{-1}$  suggesting that no further deceleration took place because the ejecta broke free of the wind and continued their expansion in the surrounding space. The fact that the sharpening of H $\alpha$  continued for months in V407 Cyg, supports the notion that the wind of its secondary extended over larger distances and carried a larger mass than for Nova Oph 2015.

#### 4 THE NATURE OF THE COOL COMPANION

At the astrometric position of the nova (A. Henden, private communication)  $\alpha=17:29:13.416$   $\delta=-18:46:13.80$  ( $\pm 0.030$  arcsec on both axes), corresponding to galactic coordinates  $l=6^\circ.6426$ ,  $b=8^\circ.5757$ , there is no entry in neither the 2MASS or AllWISE infrared catalogs, nor in GSC, PPMX or Nomad optical ones. They all list a few sources within some arcsec from the nova, but they are all distinct from the nova as proved by direct imaging.

The total Galactic extinction in the direction of the nova is  $A_J=0.51$ ,  $A_H=0.33$ , and  $A_K=0.21$ , averaging the values from Schlegel et al. (1998) and Schlafly & Finkbeiner

(2011) maps. This agrees with the reddening derived from the diffuse interstellar band at 6614 Å, for which we have measured an equivalent width of 0.118 Å on our high resolution spectra. This corresponds to a reddening of  $E_{B-V}=0.52$  following the calibration by Munari (2014) or  $E_{B-V}=0.56$  from Kos and Zwitter (2013). For the standard  $R_V=3.1$  extinction law, the averaged  $E_{B-V}=0.54$  transforms into  $A_K=0.21$ , the same value as above. At the high Galactic latitude of the nova, the line of sight exits the Galactic Thin Disk  $\sim 1$  kpc from the Sun (having accumulated up to that point  $E_{B-V}\sim 0.25$  for standard galactic extinction models), travels through some relatively empty space and then reaches the Bulge. A partnership with the Bulge is far more probable for two basic reasons: (i) the nova seems too faint (the extinction corrected value at maximum is  $V_o^{\max}\sim 7.6$ ) for a distance within the Galactic disk, and (ii) the extinction measured for the nova is too large to be generated within the Galactic disk alone and instead perfectly matches the total Galactic extinction along the line of sight. A location within the Galactic Bulge would result in an absolute  $M_V=-7.1$  mag, a reasonable value for the moderately slow decline-rate displayed by this nova (Downes & Duerbeck 2000). It is worth noticing that the statistics of the nova population in the M31 Andromeda galaxy place the large majority of them within its bulge (Shafter & Irby 2001, Williams et al. 2014).

The limits for completeness of 2MASS detections around the nova are  $J\sim 16.6$ ,  $H\sim 15.6$  and  $K\sim 15.2$ , as derived by inspection of the histograms of stellar counts vs magnitude for sources within 5 arcmin of the nova. Under an extinction of  $A_K=0.21$ , an early-K giant located in the Galactic Bulge would shine at  $K\sim 13$ , an early M giant at  $K\sim 10.5$ , and a late M giant at  $K\sim 7.5$  (Koornneef 1983, Frogel & Whitford 1987, Sowell et al. 2007), amply within the completeness limit for 2MASS. This excludes a giant as the donor star in Nova Oph 2015, while leaves open the possibility for a sub-giant. The wind of a sub-giant should extend much less than for a giant, which agrees well with our scenario that the circumstellar medium around Nova Oph 2015 was overrun by the nova ejecta much earlier than for RS Oph and V407 Cyg.

#### 5 DISCUSSION

Nova Oph 2015 is probably the first time that an FeII-type eruption is seen in a system containing an evolved secondary. In the other cases, like RS Oph and V407 Cyg, the nova eruptions have been of the He/N-type. An FeII-type for Nova Oph 2015 nicely agrees with its partnership to the Galactic Bulge, where FeII-types are almost exclusively observed while He/N-types are generally confined to the Galactic Disk (Della Valle & Livio 1998).

The He/N type novae with evolved companions are characterized by such a rapid rise to maximum that it is easy to miss observationally. Nova Oph 2015 has been instead discovered two weeks before optical maximum. Being discovered several days before reaching maximum is ordinary for FeII novae, a period of time spent in completing the rise in brightness with usually a brief pause termed “pre-maximum halt” (McLaughlin 1960). What is not ordinary is the fact that observed portion of the pre-maximum halt in

Nova Oph 2015 lasted  $\sim$ 8 days, longer than traditionally observed (Payne-Gaposchkin 1964, Warner 1995, Hounsell et al. 2010). Such a long lasting pre-maximum plateau could be the result of an apparent balance between the decline in brightness of the recombining wind (after the ionization by the initial UV-flash) and the rise in brightness of the expanding nova ejecta.

A distinguishing feature of Nova Oph 2015 is the luminosity classification of its secondary star: not a giant or supergiant (no 2MASS detection), and unlikely to be a main sequence (because of the presence of a thick and slow wind), which leaves open only the possibility that it is a sub-giant. A star evolves much faster through the sub-giant period than during the following giant phase and loses mass at a much lower rate, which would explain the paucity of known WD + sub-giants among novae. This poses the question on how the mass is transferred from the sub-giant to the WD: by capture from its wind or via Roche lobe overflow through L1? The radius of a star evolving through the sub-giant phase rapidly expands from that of a main sequence to that of a giant. This means that, for a given orbital separation, it would match the requirement for Roche-lobe filling only briefly. Before that the system would have been probably dormant, a main sequence star being unable to transfer mass via wind to the WD companion. After that, the expansion in radius of the secondary would bring the binary system under common-envelope conditions.

Given its rarity, it will be important to assess the evolutionary status of the secondary star of Nova Oph 2015. It could be derived by post-outburst IR observations (deeper than 2MASS), when the system will have returned to quiescence conditions, with the results compared to theoretical isochrones. If protracted over time, these IR observations would allow to search for ellipsoidal modulation of the lightcurve betraying a Roche-lobe filling secondary, in which case the orbital period may be expected to be (much) shorter than in RS Oph (456 days) and of the order of some weeks to a few months.

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